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ORIGINAL RESEARCH

A case study of environmental considerations and opportunities in cyber physical systems

Mario Cortes-Cornax[1] | **Paula Lago**[2] | **Claudia Roncancio**[1]

[1]University Grenoble Alpes, CNRS, Inria, Grenoble INP, LIG, Grenoble, France

[2]Department of Electrical and Computer Engineering, Concordia University, Montreal, Quebec, Canada

Correspondence

Mario Cortes-Cornax, Laboratoire d'Informatique de Grenoble, SIGMA Team, IMAG Building, 700 Avenue Centrale, Saint-Martin-d'Hères 38401, France.
Email: mario.cortes-cornax@univ-grenoble-alpes.fr

Abstract

Cyber Physical Systems (CPS) are becoming more ubiquitous, complex and powerful as well as more and more present in our daily life. The inherent benefit and comfort come with an environmental impact at every step of their life-cycle. This impact is significant and unfortunately often ignored today. As cyber-physical systems tend to be 'invisible', there is a need for awareness of the underlying infrastructure and required resources, early in the design phases. In this article, the environmental impact considerations in the early stages of the implementation and opportunities to improve design choices with a people-planet-system perspective are discussed. The authors discuss the aspects related to system configuration, data management and the overall goal and functionalities supported by the CPS. Through a specific smart home case, the potential of considering life-cycle assessment of both the devices and data management is illustrated. By explicitly considering different configurations, it will be possible to analyse the environmental impacts of the design decisions. Our research in progress targets a design approach to converge into an equilibrium between utility, performance, and minor environmental impact of smart systems.

KEYWORDS

cyber-physical systems, data flow analysis, design engineering, environmental monitoring (geophysics), Internet of Things, ISO standards

1 | INTRODUCTION AND OBJECTIVES

Cyber Physical Systems (CPS) are becoming part of critical infrastructures for a large variety of contexts including industry and our daily life (e.g. supply chain management, smart cities, cars etc.). According to the 2020 Cisco Report [1], Machine-to-machine (M2M) connections will nearly attempt 15 billion devices in 2023. Among them, connected home applications will have nearly half of the M2M share, which corresponds to 1.8 M2M connections for each member of the global population. However, the inherent benefits and comfort offered by CPS are accompanied by an environmental impact (carbon footprint, biotic/abiotic resource depletion, water footprint etc) generated over the whole life-cycle of the systems, environmental impact that is often not considered [2]. Physical devices and the complex infrastructures necessary to manage and to exploit the huge amount of produced data, at the edge or at a cloud, should also be considered when analysing the impact in the context of CPS [3].

Life-cycle assessment (LCA) is a systematic, standardised (ISO 14,040 [4]) approach to quantify the potential environmental impacts of a product or service that occur from raw materials extraction to their end of life. LCA is one of the methods to better understand and address environmental impacts, as it aims at providing a global analysis of the studied product or service. As CPS services rely on sensors, actuators, network infrastructure, and other devices, their LCA should include all of them despite the complexity. The analysis could go further by also considering the data life-cycle, as the data generated by these devices needs to be transferred, processed and stored, as it may imply the use of Big Data management systems.

The purpose of this work is to bring the environmental impact assessment as best practice in the context of CPS.

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Disclosing the infrastructure and information life-cycle assessment may help analyse CPS's trade-offs. We aim to question the 'more is better' approach which is popular in the context of CPS and largely supported by the technological and economical feasibility, among other reasons. The idea is to move towards eco-friendly smart systems by design, in order to converge into an equilibrium between benefit and environmental impact. In this paper, we point out how device management, data management and system management contribute to the environmental footprint of CPS. We argue that these aspects should be considered as part of the *first design decisions* together with the functional analysis and expected benefits. Note that even if we adopt a life-cycle perspective, we are not aiming to do an LCA of a CPS in this paper. We go beyond this method questioning, for example, the actual functionality of the CPS and studying the impact of several configuration choices and associated data pipelines.

In the following, we first introduce related work in Section 2. We then present in Section 3 a case study as an example to raise awareness that even for apparently simple services, the required system support becomes non-negligible when we consider their use at a large scale (instances and time span[1]) and environmental criteria. Such criteria are for example, the greenhouse gas reduction requirements and, more generally, planet boundaries. We present the analysis criteria along three dimensions: in Section 4 system configuration aspects, Section 5 focuses on data related aspects and Section 6 treats functional aspects. We conclude and present some research perspectives in Section 7.

2 | RELATED WORK

Environmental concerns have been considered in several contexts, leading to methods for measuring and estimating the environmental impact of different industries. Life-cycle assessment (LCA) is a well known, systematic and standardised (ISO 14,040 [4]) approach to quantify the potential environmental impacts of a product or service that occur from raw materials extraction to their end of life. The 1400 ISO standard family[2] is intended to help companies and organisations to manage their environmental responsibilities.

LCA includes four phases. The first one is devoted to the **goal and scope definition**. This phase defines, among others, the analysed function (e.g. lighting a room), the so-called functional unit (e.g. 500 h of 1000 lumen light) or the selection of alternatives (e.g. incandescent, fluorescent, or led). The scope depends on the subject and the intended use of the study [4]. The second phase, **inventory analysis**, aims at quantifying the environmental impact in terms of different aspects, such as raw material, energy use, and atmospheric emissions over the entire life cycle of the product (or service). The third step, **impact assessment**, evaluates the potential environmental and human health impacts resulting from the elementary flows determined in the previous step. The **interpretation** phase is realised in parallel with the other three. As the ISO standard has a general purpose it can be used differently by practitioners and be adapted to the domain assessment. As mentioned in ref. [5], further guidance is needed for consistency and quality assurance. The authors propose a number of tools classified by a confidence level, depending on the studied domain. In the same line, the Boavizta methodology [6], relies on LCA to provide a specific approach for measuring the impact of digital technology (i.e. data centres) in an organisation.

Regarding Information and Communications Technology (ICT) in general, in ref. [3] the authors argue that current estimations of the impact of ICT on climate are underestimated and point out the necessity of working to keep greenhouse gas emissions low. In ref. [2], the authors provide an extensive literature review on the environmental footprint of IoT and present a study (based on the LCA methodology) of the carbon footprint of the production of a wide range of IoT edge devices. Unfortunately, today it is still hard to find the device's environmental impact information. Concerning electric and electronic devices, the *Product Environmental Profile* (PEP) provides quantified and multi-criteria environmental data obtained from LCA calculation according to the ISO standard [4]. However, this information remains scarce and most manufacturers of consumer devices do not report their environmental impact following a life-cycle analysis.

As shown in ref. [2], it is important to consider a systemic view to achieve precise estimations. Therefore, it is also important to measure the impact not only of the devices that compose a system, but also of the impact of the data. For instance, in ref. [7] the authors provide guidelines for measuring the impact of training and using AI models in the cloud. The need of considering a holistic view for IoT-based systems is exemplified by the work of Ipsen et al., [8]. This study presents an extensive work that quantifies the environmental performance of seven smart city solutions at an urban system level and evaluates their contribution to develop environmentally sustainable urban systems. The authors use the so-called urban metabolism-life cycle assessment (UM-LCA) approach. The study reveals that the introduction of smart solutions (like smart energy metres) to a city generally 'has a negative influence on the environmental sustainability performance', calling for a need of optimising the designs to fit the intentions.

In this paper, we discuss several aspects of CPS with an environmental perspective and show how they can be considered from the design phase. We rely on a smart home use case presented in the next section to illustrate our findings. This paper extends [9], a position paper where we presented the first steps of our work.

3 | A SMART HOME CASE STUDY

As mentioned before, the brutal expansion of connected devices enables many services but raises questions about the net benefit of CPS systems when considering the environmental

[1] for example, millions of smart buildings during many years
[2] https://www.iso.org/iso-14,001-environmental-management.html

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TABLE 1 Sensors installed in A4H.

Type	Measures	Count
Environmental sensors	CO_2, Humidity, temperature, noise, brightness, and presence in each room	23
Lamp sensors	Monitor state, light levels and colour (hue)	22
Contact sensors	Monitor doors, windows and cabinets	21
Energy/water sensors	Monitor instant and total consumption at each point	20
Smart outlet	Monitor appliance state (most unused)	16
Interaction devices	Interrupters and remote controls. Monitor interactions with a controlled device	15
Shutter sensors	To control shutter opening level	8
Pressure sensor	Monitor presence in bed	1
Loud speaker	Registers songs played	1

impact of their life-cycle. For instance, Smart Homes include several connected devices to provide a wide range of services from management of water or electricity consumption to services for comfort like light or music management [10]. Questions also arise with other smart devices that are always connected and waiting for a 'command'. Although their individual manufacturing cost and consumption is generally low, when considering the whole system and the life-cycle of all devices, the impact is no longer insignificant.

In the following, we introduce a case study to raise awareness that even for apparently simple services, the required system support becomes non-negligible when considering their use at a *large scale* and regarding environmental criteria (e.g. CO_2 emissions, water consumption, and abiotic depletion). With *large scale* we refer to both, the number of instances and the time they operate: millions of devices implementing smart homes (buildings, services etc) during many years. Considering environmental sustainability performance becomes necessary, so as to retain 'smart solutions' which fit the intentions without causing hidden or indirect damages.

We use a smart home case to illustrate our purpose. Amiqual4Home [11], designated by A4H in the following, is an experimental apartment[3] configured to unobtrusively monitor its consumption (e.g. electricity) and the inhabitant daily living activities such as cooking, sleeping or washing dishes. It is a two-story, one-bedroom, one-office, and two-bathroom apartment equipped with 219 sensors and actuators. The devices are listed in Table 1.

Figure 1 shows a simplified illustration of the architecture. A local server stores and analyses sensor data and communicates back with actuators when needed. Raw data, as well as processed data, can be stored in different formats, for extended periods of time. Sensors in A4H use different M2M communication protocols (e.g. KNX and MQQT). Most of them use a hub or gateway to create a sensor network.

Redundant sensors were installed in A4H to make the system more robust and to create a versatile dataset that could be used by researchers in different areas. This configuration is related to functional requirements. The ContextAct@A4H dataset [12] contains the data captured by all the sensors in a 3-week free-living experiment annotated with activity labels. In this experiment, the considered functional service was monitoring elder people activities at home, to support their independence at home while still alerting a support network of unusual behaviours or events. Other similar projects exist such as refs. [13–16].

To analyse the environmental costs, benefits and improvement opportunities, we consider topics related to system configuration, data footprint and the functional point of view. They are presented in Sections 4, 5, and 6 respectively. We use a subsystem of A4H (the contact sensors) to illustrate the potential impact of different design choices.

4 | SYSTEM CONFIGURATION ASPECTS

Analysing the environmental impact requires, among others, the definition of the scope of the study and the perimeter of the system with the corresponding inventory of the devices composing it. In A4H, in addition to sensing and communication devices (gateways and routers), user devices (a smartphone and a tablet) were used to monitor the infrastructure and as a control panel for the house. Together, they compose the smart home's infrastructure, which may be configured in different ways. The sensors installed at A4H are listed in Table 1 but our study will focus on the contact sensors together with the required gateway and PC (illustrated in Figure 1).

Multiple factors and trade-offs are involved in choosing a system configuration, including device complexity and additional services they might provide [2]. We argue that their expected lifetime and environmental impact are also important in the decision. In this section, we present some attention points concerning the system configuration that may help designers to incorporate environmental impact analysis as first-class citizen when designing CPS.

[3] A4H has an area of 87 m^2. The reader may refer to [11] for more information.

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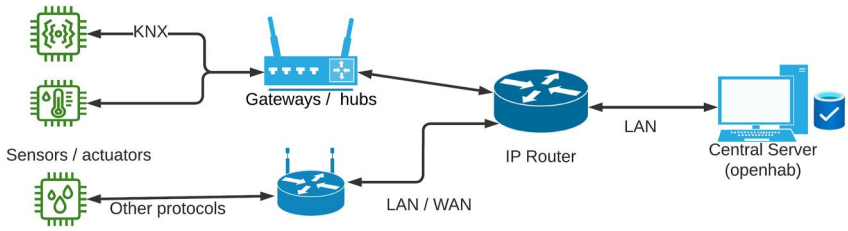

FIGURE 1 General architecture of the data collection system of A4H.

TABLE 2 Primary energy (in kWh) used in the life-cycle (Manufacturing, Distribution, Use, End-of-life) of devices composing the A4H sub-system.

Device	Estimated life time	Energy use life time (kWh)	Energy of life-cycle without use phase (kWh)	Total (kWh)
H-IP gateway [19]	10 years	755,56	38,44	794
H-contact sensor [17]	10 years	0,48	3,77	4.25
S-IP gateway [20]	10 years	177,5	5,5	183
S-contact sensor [18]	10 years	0[a]	14,25	14.25

[a]Reported as 0 by the manufacturer, it is <0,01% of the total life-cycle.

4.1 | Devices and environmental profile

Deciding which and how many devices should be installed in a smart home is a key decision. The number of devices can quickly grow, but the extra benefits can be minimal. Identifying the precise functional requirements and appropriate precision and fault-tolerance will help when choosing the devices. For example, in A4H, there were smart switches, smart energy metres and lighting sensors. All of these can measure whether the lights on one room are on or off with different granularity. While the smart switch can only tell the state of the light, the other two provide a more continuous measure. The choice of the devices implies different environmental impacts depending on their complexity and manufacturing conditions, among others, which should be considered along with the functional requirements [2].

It is important to highlight that the life-cycle of a device includes the material extraction, manufacturing, transportation, use, maintenance and end-of-life. On each phase, there is an environmental impact. As mentioned before, it is still hard to find this information of devices, even if some manufacturers have agreed to disclose *Product Environmental Profiles*, *PEP*, for their devices. In this paper, we rely on PEPs to analyse device's environmental impact focussing on the estimated energy consumption[4]. The PEP documents of the devices can be used in the design phase of smart services to compare different alternatives and manufacturers. In the following, we illustrate some interesting information that can be found in the PEP documents.

4.1.1 | Sub-system example in A4H

For our study, we use a sub-system installed in the smart home, for which PEP or trusted environmental impact information of the devices were available. The architecture is the one illustrated in Figure 1 where the sensing part corresponds to the contact-sensors of the apartment.

We refer to the PEP published by Hager and Schneider for their contact sensors [17, 18], the KNX gateway [19, 20], and various configurations of Fujitsu Computers [21]. The mentioned manufacturers are referred hereafter as H, S, and F respectively. Note that the purpose of this paper is a general discussion and not to put forward one product or another. For the PC, we also used data provided by EcoDiag, a calculator maintained by the EcoInfo team of the CNRS French public research centre[5].

In Table 2, we show the energy consumption estimated for the use phase and for the total life-cycle of the devices, which includes manufacturing, distribution, use and end-of-life[6]. A difference of more than x4 is observed between the energy consumed in the 10 years use phase (expected lifetime reported in the PEP) between the studied gateways. An order of x6 is observed when considering only the other life-cycle phases. The H-IP Gateway is more complex and provides more functionalities. These aspects can be considered by designers to choose the more suitable devices for the configuration so as to find the best fit with respect of the functionality requirements and minimising the environmental impact.

4.2 | Lifetime and use phase

The expected life-time of an item is considered as the period of time when it can be used. This information is important to be taken into account in order to study the maintainability of the system and it's global impact. If there is a difference between life-times of dependant devices (for instance, gateways, and sensors) this could produce situations where the longer life

[4]A multi-criteria analysis is necessary for a full understanding of the environmental impact but it is out of the scope of this paper.

[5]https://ecoinfo.cnrs.fr/ecodiag-calcul/

[6]No information about maintenance was available

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TABLE 3 Total use of primary energy (in kWh) in the use life-time of different PC configurations.

Computer	Estimated life time	Energy use lifetime (kWh)
Average PC[a]	5 years	945
Fu - PC max configuration [21]	5 years	535
Fu - PC standard configuration [21]	5 years	165

Note: The energy consumed for the total life-cycle of the product was not available.
[a]Estimated using EcoDiag calculator available at https://ecoinfo.cnrs.fr/ecodiagcalcul/.

TABLE 4 Examples of configuration alternatives and energy consumption during a 10 years **use phase**. 2 PCs are needed as their expected life-time is 5 years.

Monitoring	Configuration	Energy use lifetime (kWh)
Apartment doors and windows	1. Average PC, 21 H-contact sensors, 1 H-gateway	2655,5
	2. Fu. PC max conf., 21 H-contact sensors, 1 H-gateway	1781,53
	3. Fu. PC standard, 21 H-contact sensors, 1 S-gateway	517,5
Entrance and back doors	4. Fu. PC standard, **2** H-contact sensors, 1 S-gateway	508,5
	5. Config. 4 with PC only with 50% dedication	343,45

device has to be replaced before its lifetime because the shorter life device is broken and devices compatible with the longer life device are not available anymore.

Considering the sub-system example in A4H, the expected lifetime of PCs reported in the manufacturer's document (not a PEP) is 5 years. The expected lifetime reported in the PEP documents of the different sensors and gateways is 10 years. In Table 3, we present the estimated energy consumed[7] during the use phase of different PC configurations.

As mentioned before devices' lifetime plays an important role when studying its life-cycle overall impact. For many electronic devices, manufacturing is the phase with more environmental impact. In Table 2 we note that for the S-Contact sensor, the energy consumed during use phase is considered insignificant by the manufacturer. However, the energy consumed in the use phase during the whole life-time can become the one with the more impact. For instance, in Table 2, regarding both gateways, the weight of the energy consumed during the use phase (considered over 10 years) becomes more relevant.

While the considerations might be multiple when choosing a device, including their complexity and additional services they might provide [2], their environmental impact should be included in any decision framework.

4.3 | Sub-system function and configurations

In addition to an individual analysis of devices, an interesting way of studying the system's impact is to compare different configurations while explicitly showing their environmental impact. Here, we consider primary energy in kWh, which will then be computed in CO_2 equivalent in the next section considering the so-called energy mix. Important differences between the configurations may be noticed, as illustrated with our A4H use case.

4.3.1 | Sub-system example in A4H

In Table 4, we show five configurations considering various combinations of sensors, gateway and PC and their estimated energy footprint. Configurations 1 to 3 monitor all the doors and windows of the apartment whereas configuration 4 targets exclusively the front and back doors. Configuration 5 uses the same configuration as 4 but considering that the PC is only 50% dedicated as a hub. In Table 4 and Figure 2, configurations 1–4 consider the PC as totally dedicated to the sub-system treatment, which is unrealistic. Indeed, the PC is used as server for all the devices installed in the apartment and for some other tasks. For a precise analysis, the 'cost' of the PC has to be distributed over all the tasks it serves. A fine grained study could be done to estimate the percentage of dedicated energy for a specific task as proposed in the Boavizta methodology concerning virtual machines in data-centres [6]. To illustrate that purpose we show configuration 5 with 50% PC dedication. It can be observed that the impact of the PC is important, so the dedication (100%, 50% or less) has a big impact. Also, as we consider here only the use phase, the consumption of the sensors is negligible. We also highlight that the type of gateway may have a great impact (configurations 1 and 2 vs. the others). For the use phase of the configurations, we consider here the expected lifetime of the devices that is 10 years. As the expected lifetime of a PC is only 5 years, two PCs are necessary to cover the whole period in all the configurations.

[7]The energy consumption presented in this paper is estimated using the documents referenced in this Section.

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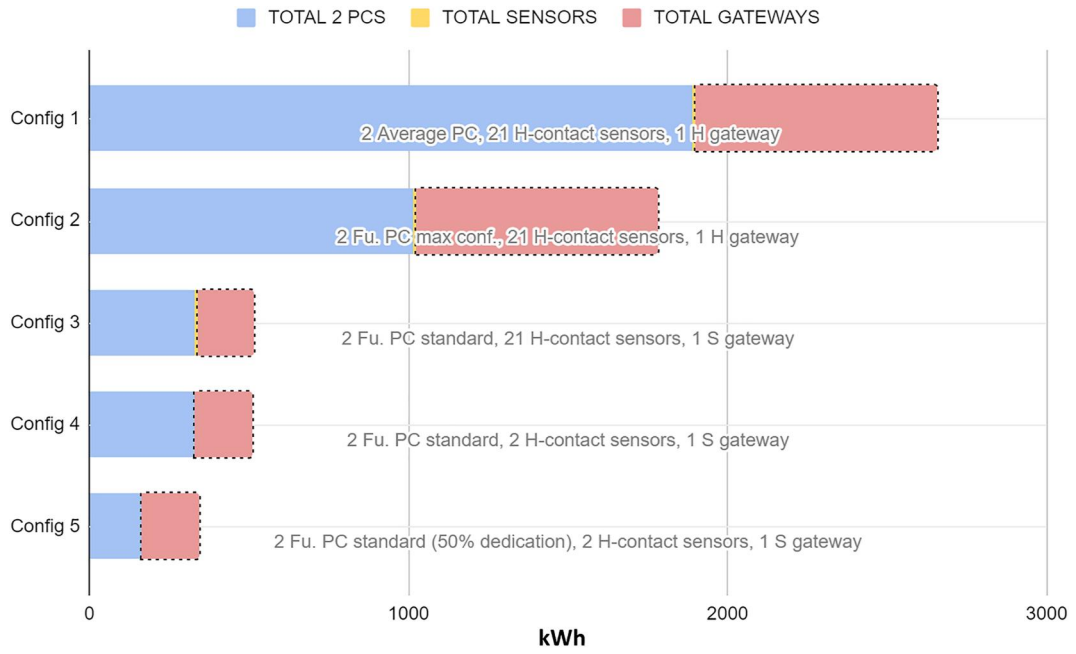

FIGURE 2 Primary energy consumption during 0 years **use phase** considering the different configurations.

4.4 | Multi-criteria analysis and energy mix

Although multi-criteria analysis is necessary (and available in the PEP used in this study), it will not be developed in this paper[8]. Our aim is to point out the impact of some decisions in the environmental impact and how it can grow exponentially. The energy consumption criterion allows us to discuss this in simple terms.

Other criteria as resource depletion and the CO_2 footprint are, of course, also important. It is worth noting that the CO_2 footprint of the electricity depends on the so-called energy mix. This factor is time and location specific, it evolves in time and differs from one country to another and even from one region to another in some countries.

According to ElectricityMap [22], accessed on January 30, 2023 at 18pm GMT, at that moment, the estimated equivalent CO_2 for a kwh (gCO_2eqkWh) is 0.088 $kgCO_2eqkWh$ in France (mostly nuclear), whereas it is only 0.027 $kgCO_2eqkWh$ in Quebec (mostly hydraulic). We note that in Australia there is a big difference between Tasmania Island (hydraulic) versus Queensland (mostly coal), reporting 0.212 and 0.749 $kgCO_2eqkWh$ respectively. The aforementioned data may rapidly change depending on different factors as the season, the weather conditions and the geopolitical situation. For instance, Flinders Island in Australia reported $27gCO_2eqkWh$ the 24th March at 11am GMT and in the moment we are writing these words (January 30, 2023 at 18pm GMT), $648gCO_2eqkWh$ were reported.

[8]A complete LCA is out of the scope of this paper.

4.4.1 | Sub-system example in A4H

Considering the system configurations presented before, Table 5 illustrates the differences in terms of CO_2 impact depending on the energy-mix available during the use phase. The values presented in the table are a projection of the current equivalence for the whole lifetime in three locations. More precise projections could be considered by taking into account the data history. The table points out the potential important differences induced by the place where the system is used. This difference also appears during the other life-cycle phases. The CO_2 impact of the manufacturing of devices is related to the energy-mix of the location where it takes place.

The presented topics are discussed to nourish the analysis and opportunities of action for designers and users. Hardware, network and embedded system aspects for energy reduction, for example, are not discussed here but best choices are of course expected to be retained with the goal of a global improvement of the environmental impact.

5 | ANALYSING THE CPS DATA FOOTPRINT

The environmental impact of Cyber-Physical systems is not only related to the impact of the devices they use, but also to the treatment of the data it produces. Certainly, the energy used by the devices in the configurations shown in the previous section considers an average value, but it depends on the volume and type of sensed data. Becoming aware of the data-life cycle reveals the cost and impact of data management to make adapted choices and avoid voracious designs.

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Delineating the data life-cycle: the benefits of many CPS come from the analysis of the sensed data. Data follows a life-cycle, summarised in Figure 3, including its acquisition, transmission, processing, storage, use and end of life (archive and deletion). Each stage of the life-cycle has a cost and system design decisions can change the global environmental impact.

Data acquisition: we refer here to sensed data where the sensors *sampling rate* determines the volume of data produced and transmitted. The volume of data is directly proportional to the energy required. Sampling rate can be set in Hz (samples per second) or configured to send a new measure on an event based manner. Algorithms used to analyse the data need to adapt to the sampling approach, for example, by using different windows of analysis [23]. The point becoming important is to avoid wasting resources by choosing a 'good enough' level of data collection.

Considering A4H, sample rate aspects are illustrated in the sub-system example used in the previous section. We estimate the volume of data produced by the 21 contact sensors of A4H during 10 years (expected lifetime) with four sampling approaches. Table 6 shows three periodic sampling approaches and an *event-based* approach. The *event-based* sampling approach represents the scenario where the device sends data only when a state change occurs (open/close the door). Relying on the 3-week experiment of A4H logged in the ContextAct@A4H dataset [12], we observe an average of seven events per day per device and a maximum of 128 events per day per device.

For all the sampling scenarios, a sensor measure is represented as a tuple: < *timestamp*, *sensor_id*, *value* >. The values are integers and we ignore any protocol overhead. The size of a tuple is 12 Bytes. Tuples could be much larger depending on the data representation chosen in the system.

Data transmission: data is transferred from the sensing devices to the processing centre at a cloud or, as in A4H, at the edge. Globally, the architecture for data management ranges from in device treatment, edge processing to hybrid or completely cloud-based systems.

The choice of the *network protocol* (some protocols are more energy efficient than others) and the transmission strategy

TABLE 5 Examples of estimated CO_2 footprint of the use phase of the studied configurations in three locations.

Configuration	France/0.088 $kgCO_2eqkWh$	Quebec/0.027 $kgCO_2eqkWh$	Queensland/0.749 $kgCO_2eqkWh$
1. Average PC, 21 H-contact sensors, 1 H-gateway	233,69	71,70	1988,99
2. Fu. PC max conf., 21 H-contact sensors, 1 H-gateway	156,77	48,10	1334,37
3. Fu. PC standard, 21 H-contact sensors, 1 S-gateway	45,54	13,97	387,59
4. Fu. PC standard, 2 H-contact sensors, 1 S-gateway	44,74	13,73	380,83
5. Fu. PC standard (50% dedication), 2 H-contact sensors, 1 S-gateway	30,22	9,27	357,24

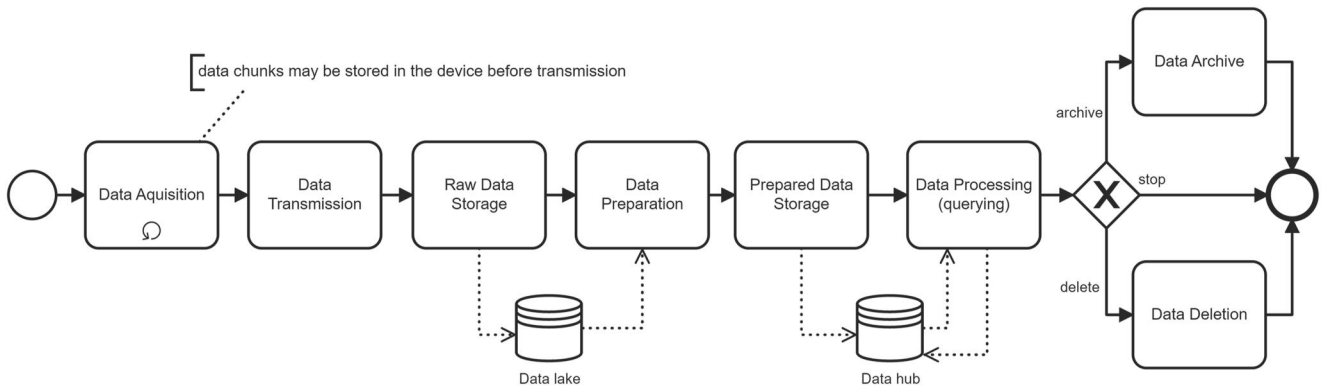

FIGURE 3 Simplified data pipe-line from data acquisition through different possible treatments.

TABLE 6 Estimated data produced by contact sensors in the ContextAct@A4H experience.

Sampling approach	10 years sensor data	10 years apart. sensors data
Sampling rate, 1 measure/second	3786.83 MB	79.52 GB
Sampling rate, 1 measure/minute	63.07 MB	1.32 GB
Sampling rate, 2 measure/minute	126.14 MB	2.65 GB
Event based, average, 7 measures/day	0.306 MB	0.006 GB
Event based, max, 128 measures/day	5.6 MB	0.117 GB

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play a role in resource consumption. Functional requirements may guide transmission strategy. While in some contexts it is necessary to transmit data immediately, for other use cases, data chunks can be 'accumulated' in the device until the data packet is complete. Such configurations usually improve data transmissions and it is worth not neglecting.

In A4H, different transmission protocols were used: KnX, MQQT, Wifi, Bluetooth and Zigbee. The power consumption of these protocols differ so as their data range. While the specifics are out of the scope of this article, it is an important consideration in the design of CPS. In A4H, there was no consideration of energy consumption at the moment of decision. The decision was made considering device capabilities, availability and technology testing purposes. The data was transmitted immediately in most cases as the devices did not have storage capacity.

Data preparation: refers to the transformations to make data suitable for queries, inferences etc. This might include resampling to align the sampling rate of various sensors, ordering of events, data representation transformations or window aggregations to, for instance, obtain average values within a time window. The results of such preparation might be stored in a data hub. At this step, the energy impact is related to the algorithms used for such transformations, as well as with the volume of data to handle.

In A4H, each sensor event was first transformed to a tuple of the form < *timestamp*, *sensor*$_i$*d*, *value* > by the middleware (OpenHAB). This was done at the central computer of the architecture and logged in a file. Then, to recognise activities, the log was transformed into the SEQ format accepted by the complex event analyser tool. We refer the reader to [11] for more details. The results of activity detection were stored for pattern analysis.

Data querying and analysis: refers to the inferences made from sensed data. Inference algorithms range from simple rules for aggregating data to deep learning algorithms. The choice of algorithm should align with the goal of the system and the uncertainty of the sensors. Here, it is worth to question the benefit of using a more 'expensive' algorithm regarding the use case.

In A4H, activities were recognised using a logic-based approach with model checking. Contextual behaviour patterns were analysed with an online sequence mining algorithm [24]. The model checking approach allowed activities to be recognised using a formal definition of the complex event. For example, if the shower door is open and then closed and the shower water is running, then the 'taking shower' activity is recognised [12]. Other authors use machine learning approaches which require training a model with previous data. While the ML approach might be less sensitive to sensor inaccuracies, the logic based approach does not require the training phase which can be computationally, and energy expensive. The accuracy of the model-checking approach was considered suitable for the application requirements.

Data storage and end-of-life: sensed data is stored at different stages and potentially in different forms, leading to several replicas or 'approximate' replicas. The resources used for storage need to be related to the impact of the CPS. The architecture choice between cloud or edge approach, depends on system factors but is also influenced by functional factors and privacy requirements.

For example, in our A4H case study, contextual behaviour patterns were handled at an individual level, but finding patterns at the population level (for instance, for improving public health policies) would probably lead to a cloud based architecture. At A4H, raw data, activity data and behaviour patterns were stored in files in the local computer. Raw data has also been archived into cloud services. As for many services, calculating the CO2 footprint of storing data is difficult. In ref. [25], the GRICAD team of Grenoble University reports a study of the CO2 footprint of data storage in data centres located in France. They performed the LCA of three platforms with the functional unit 'Storage of 1Go of data during 1 year'. The reported results for the three platforms are approximately 11,7 gCO_2eq, 12,3 gCO_2eq and 37,9 gCO_2eq per year and per Go. The CO_2 footprint depends on many aspects such as the electricity mix, the life time of the data centre (e.g. building, servers), and the PUE of the data centre. For more information the reader may refer to [25].

We point out the importance of defining a 'data end-of-life strategy' to avoid uncontrolled growing of the amount of stored data. Such end-of-life strategy can be specified with temporal events or semantic events. For example, absolute time, relative time as N years after data creation timestamp or last use, or when the person concerned by the data passes away or move.

This list of considerations is not exhaustive but intends to raise awareness of how to consider the assessment of the data life-cycle in an analysis. Neither the analysis nor the decisions are easy, but the environmental factors should be one of the criteria considered along-side other requirements and restrictions like privacy, costs, and functional requirements.

6 | ANALYSING SYSTEM FUNCTIONALITY

We have discussed how system configuration and data decisions can impact the environmental footprint of IoT based systems. It shows how decision making to choose one configuration or another can integrate the environmental aspects and be guided by functional priorities. Mindless consumption and services that offer little added value to the user may led to devices that are not 'really' useful and are discarded after few months. If the devices are not re-used, the environmental cost of their manufacturing is paid without almost no 'functional' benefit. As system designers, questioning the benefit for the user of having more devices or powerful configurations is important to avoid as much as possible these scenarios.

Contrary to energy consumption or monetary criteria, we still do not have a generic quantitative indicator of usefulness or worthiness of a service or a functionality. Nevertheless, without intending to be exhaustive, some functionality related aspects are presented hereafter to better target IoT-based services by performing requirements analysis. Simply speaking, the point is

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to be conscious of the environmental impact of such systems so as to pay the cost for the cases where it is worth doing so.

Functionality and purpose: is the IoT-based system used to implement a functionality that is clearly identified? Is this functionality responding to a need that is clearly established?

For example, A4H has been used for several research studies including:

- energy consumption analysis [26] for self-reflection and improvement,
- vocal commands [27] to improve the comfort of the inhabitant,
- activity recognition [24] to infer health status based on the behaviour of the inhabitant.

Concerning activity recognition the purpose may be refined so as to target the minimal system configuration. For instance, the contact sensors installed at A4H, allowed monitoring the mobility, kitchen activity, and bathroom use patterns. But, if the concern is the person going out and getting lost, one sensor at the entrance door and one at the door leading to the patio may be sufficient.

User nature and number: what is the nature of the *user* of the system? Indeed, the *user* may be a person, an animal, a device, a system…The system can serve one single user or a set of users of the same or different nature.

In our A4H case, the CPS together with the activity recognition algorithm were designed to monitor a person living alone in the apartment. The direct *user* of the collected data is a system without providing an immediate service to the inhabitant. Also note that, if there are several inhabitants, the system would require extra devices to perform correctly.

User distance: does the system serve directly a *user* without requiring extra processing? How is the data processing workflow? In the case where extra processing is required, it would be interesting to clarify its environmental cost.

In the activity monitoring use-case, the first consumer of sensed data is a continuous process performing context and activity recognition. The second is a process that performs online contextualised pattern analysis and event notification to a *human user*, a care giver. The continuous execution of the mentioned process requires resources to be considered when analysing widely the environmental cost of the system.

Utility: considering the preceding points and the context where the functionality is intended to operate, how useful or crucial is it for the *users*? This question may be difficult to answer because of the variety of the nature of the *users*, the 'distance' and the subjectivity of the rational.

For services devoted to people, the analysis can be made considering the life domain and the functional goals, and more generally no functional goals:

- In smart homes, typical life-domains are *Health*, *Well being*, *Work/education*, *Housing*, *Leisure*, *Daily living* and *Communication* [28].
- Functional domains include *Care support*, *Organisation*, *Compensation and assistance*, *Prevention and engagement*, *Enhancement* and *Satisfaction* [28]. They can be related to Maslow's hierarchy of needs [29] to help clarifying the priorities.
- Non-functional goals such as monitoring, logging, or prediction. How and when is expected the sensed data to be used? For example, immediate use (e.g. by actuators), short term, long term, undefined…Is the data life-cycle clear (see Section 5)? What about the data end-of-life strategy?

Usefulness period: the devices composing the CPS infrastructure has an expected lifetime which determines the potential maximum duration of its use phase. How does this duration match the period during which the function is required? If this 'usefulness period' is much shorter than the expected lifetime of the components of the CPS, how reusable are them? What are the expected system maintenance actions? (e.g. device replacement). Recycling does not appear clearly as a safe solution for discarded devices [30]. For instance, the PEP document of S-contact and H-contact sensors report 27% and 39% of recycling potential. In addition, as noted in ref. [30], this process spawns additional use of energy and resources.

The proposed list of questions needs to be further refined and validated. Even in the absence of a quantitative evaluation, still, a qualitative approach could provide insides for designers and users to improve the rational for new implementations or upgrade of IoT based services.

7 | CONCLUSION AND FUTURE WORK

To conclude, it is worth stating the undeniable benefits that cyber-physical systems have brought in both the industry and our daily life in different domains, such as healthcare, supply change management, or security. Considering the huge potential of CPS and the current environmental challenges, our position is that more than ever, the choices for introducing 'smart' functions should be analysed very carefully.

Performing a Life-Cycle Assessment for a complex cyber-physical system is challenging. Nevertheless, even if a complete LCA cannot be realised, conducting an approximate study will contribute to increase the environmental responsibility and sustainability during system development. We aim at even go to a form of systemic thinking that considers both the functional definition and the environmental impact when designing solutions.

In this paper, we discussed the aspects that influence the environmental footprint of a CPS system and used a subsystem of the Amiqual4Home apartment as case study to illustrate our purposes. We distinguished between system, data and functionality related aspects to help integrating environmental analysis during the design phase. We pointed out the importance of considering the scale and the context of the deployment of the systems, as the impact of the different life-cycle phases will differ from a place to another because of the

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origin of the electricity (nuclear, carbon, renewable etc.). Concerning the use phase, it could even evolve along time. We did not discuss the rebound effects which should also be considered as the addition of a new service usually leads to other activities having their own environmental impact.

In future work, we will focus on improving the approaches in design phases so as to develop the part of environment awareness together with the actual goal of the system (comfort, health, energy savings etc.) and the induced benefits.

We will work on the evolution of design methods based on works such as ref. [31]. The use of scenarios may also be useful to enquire about the various uses of the physical infrastructure.

We put forward a big challenge to motivate actors to find the *good enough level* of services and not go to a *more is better* approach just because it is feasible from a technological and economical perspective. By explicitly providing environmental information, designers as well as users can make informed and conscious decisions in that sense.

Could we consider to have a 'fair trade' approach with a people-planet-system perspective that integrates an impact/benefit analysis including the whole life-cycle of the smart function?

AUTHOR CONTRIBUTIONS

Mario Cortes-Cornax: Conceptualisation; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualisation; Writing – original draft; Writing – review & editing. **Paula Lago**: Conceptualisation; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualisation; Writing – original draft; Writing – review & editing. **Claudia Roncancio**: Conceptualisation; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualisation; Writing – original draft; Writing – review & editing.

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CONFLICT OF INTEREST STATEMENT

I am aware that this journal requires all authors to disclose any potential sources of conflict of interest in the manuscript.

DATA AVAILABILITY STATEMENT

These data were derived from the following resources available in the public domain: https://register.pep-ecopassport.org/pep/consult https://hager.com/nl/catalogus/download/product/asset/file/PEP_HAGER_TJA470_HAGE-00444-V01.01-EN_17022020.PDF/ https://www.hager.ie/files/download/0/782901_1/0/PEP_HAGER_TRC301B_HAGE-00496-V01.01-EN_342020.PDF https://www.se.com/au/en/download/document/ENVPEP1804008EN/ https://app.electricitymap.org/map.

ORCID

Mario Cortes-Cornax https://orcid.org/0000-0003-2635-319X

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